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Squeezed Light at 2128 nm for future Gravitational-Wave Observatories

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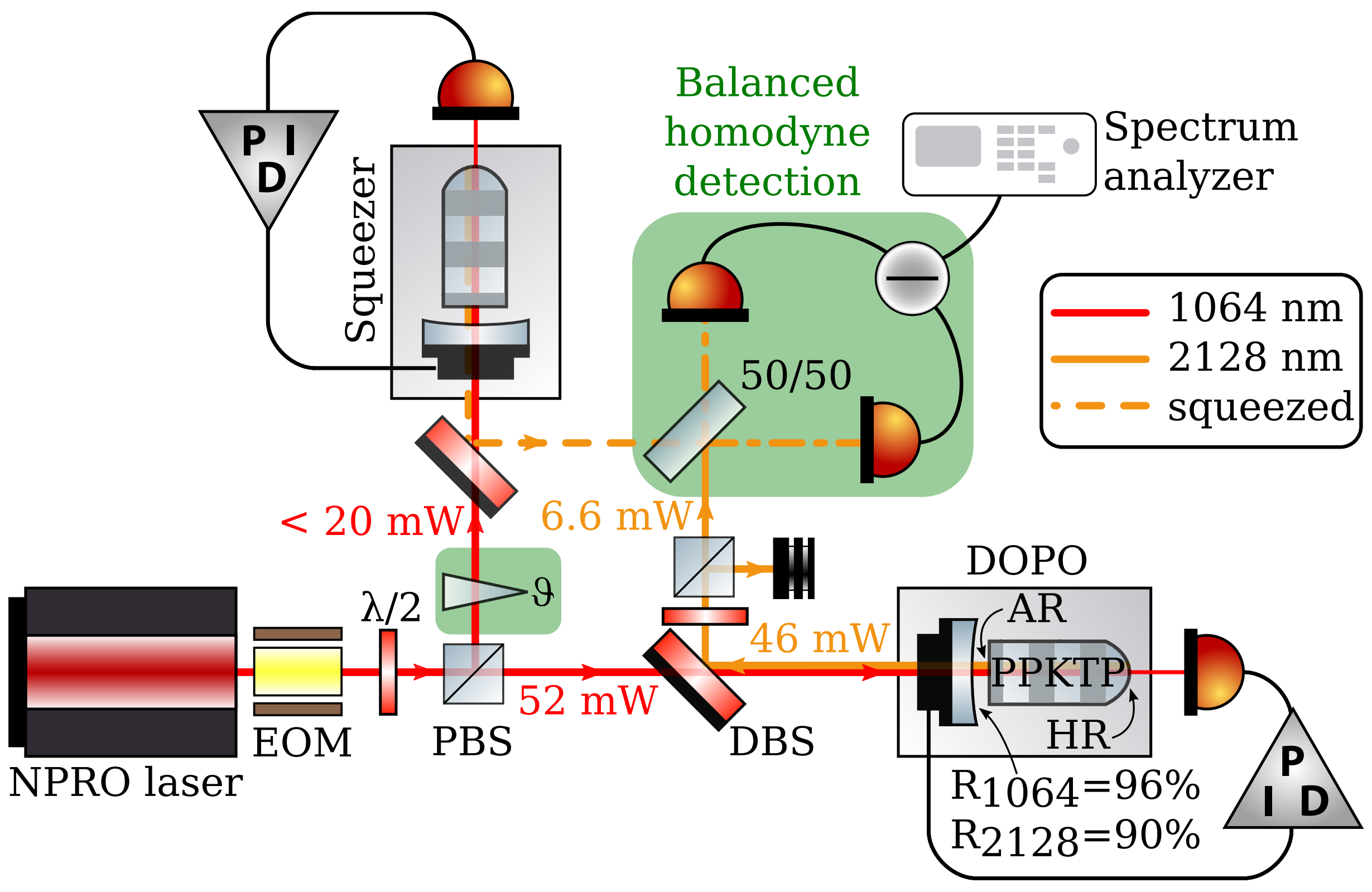
Introduction

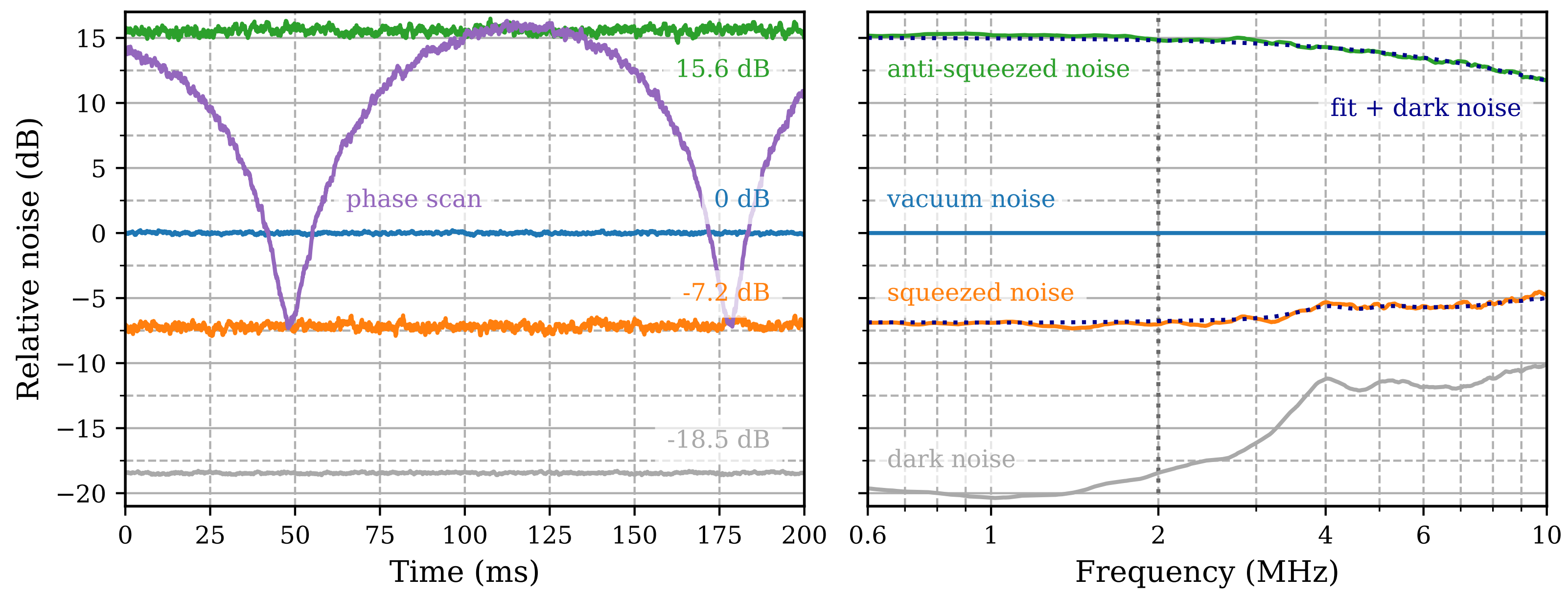
Current gravitational-wave detectors are limited by coating thermal noise in the mid-range of the detection spectrum, and by quantum noise at high frequencies. Changing the laser wavelength from 1064 nm to around 2 µm would allow the usage of silicon test masses and coatings with reduced thermal noise. All current detectors use squeezed light to reduce quantum noise [1, 2, 3], which then needs to be shifted to the new wavelength as well. Here, we report the detection of (7.2 ± 0.2) dB squeezing at 2128 nm. Different from the previous approach [5], no second harmonic generation is required because the pump light was produced directly by a nonplanar ring oscillator (NPRO) at 1064 nm. Instead, ultra-stable bright light at 2128 nm was produced by a home-built degenerate optical oscillator (DOPO) with an external conversion efficiency of greater 88 % [4].

Experimental Setup



Results

Squeezing



Left: Zero-span noise measurement at a sideband frequency of 2 MHz. We achieved a squeezed noise reduction of (7.2 ± 0.2) dB below the vacuum noise, accompanied with an anti-squeezed noise in the orthogonal quadrature of (15.6 ± 0.2) dB. The noise arches were obtained by scanning the BHD readout angle Θ.
Right: Spectrum of the generated squeezed light in the regime 0.6 MHz to 10 MHz, fitted with the following equations [6].
The squeezed $\hat{X}_1$ and anti-squeezed $\hat{X}_2$ light-field quadratures are represented by $\Delta^2 \hat{X}^m_{1,2} = \Delta^2 \hat{X}_{1,2} \cos^2 \Theta + \Delta^2 \hat{X}_{2,1} \sin^2 \Theta$, with the measured quadrature variances $\Delta^2 \hat{X}^m_{1,2}$ and Gaussian-distributed phase noise with an rms value of Θ. The quadrature variances themselves can be described by $\Delta^2 \hat{X}_{1,2} = 1 \mp \eta \frac{4\sqrt{P/P_\mathrm{thr}}}{\left(1 \pm \sqrt{P/P_\mathrm{thr}}\right)^2 + 4(\Omega/\gamma)^2}$, where the upper sign corresponds to $\hat{X}_1$ and the lower sign to $\hat{X}_2$. The variance of the vacuum ground state has been normalized to 1. P is the pump power and the threshold power is given by $P_\mathrm{thr} = 20\,\mathrm{mW}$. η is the overall detection efficiency and our squeezed-light cavity has a linewidth of $\gamma = 2\pi \times 64\,\mathrm{MHz}$. The measured sideband frequency is $\Omega = 2\pi \times 2\,\mathrm{MHz}$.

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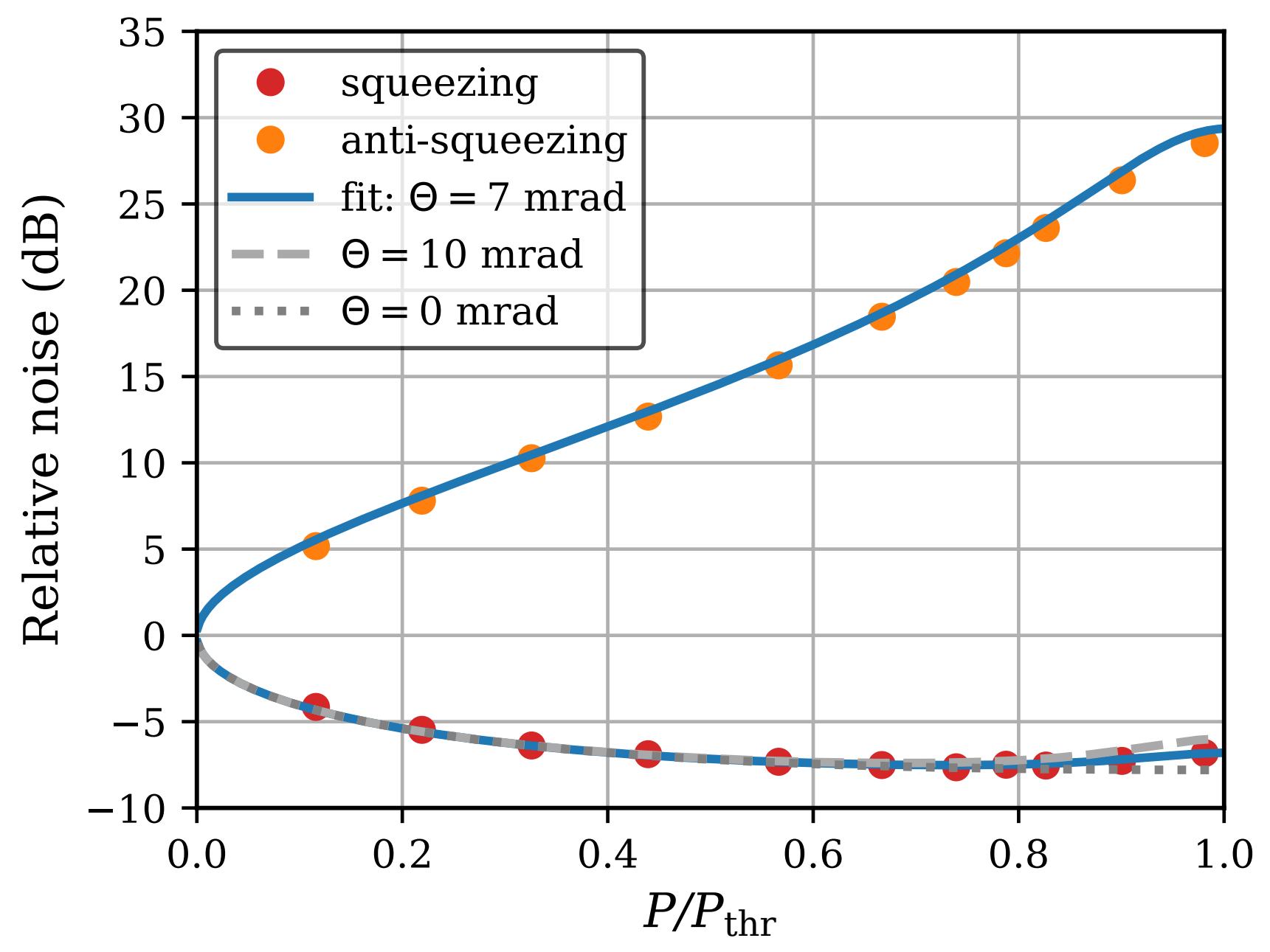
Phase Noise

To estimate our phase noise level, we measured squeezing and anti-squeezing for different pump powers. The data points were taken by using the maximum and minimum of a scan of the readout angle. The influence of the phase noise is not visible up to a pump power of about 70 % of the threshold power and we get an estimated upper limit of about 7 mrad.



Analysis of Losses

Table: Overview of optical efficiencies

Source	Efficiency (%)
Resonator escape efficiency	98 ± 1
Propagation efficiency	> 99
BHD visibility (98 ± 1) %	96 ± 2
Photodiode quantum efficiency	92 ± 3
Total value as product of estimated efficiencies	85 ± 4
Total value from squeeze and anti-squeeze values	83.9 ± 0.5

The beam overlap (visibility) between the local oscillator and squeezed beam at the balanced-homodyne detector contributes quadratically, and therefore has a high impact. The losses are dominated by quantum efficiency of the available photodiodes (Thorlabs FD05D, with windows removed).

Outlook

The concept of doubling the wavelength of the existing ultra-stable light at 1064 nm makes the 2128 nm wavelength a promising candidate for next-generation gravitational-wave detectors like Einstein Telescope and Voyager, if high quantum efficiency photo diodes with low dark noise will become available for that wavelength.

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